PAPER P-825

PRODUCTIVITY OF DEFENSE RDT&E

Charles L. Trozzo

October 1971

IDA
INSTITUTE FOR DEFENSE ANALYSES
PROGRAM ANALYSIS DIVISION

83

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UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) INSTITUTE FOR DEFENSE ANALYSES PROGRAM ANALYSIS DIVISION	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE

PRODUCTIVITY OF DEFENSE RDT&E

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Charles Trozzo

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
October 1971	78	

8a. CONTRACT OR GRANT NO. DAHC 15-67C-0011	9a. ORIGINATOR'S REPORT NUMBER(S) PAPER P-825
b. PROJECT NO. T-83	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	ODDR&E

13. ABSTRACT

This paper explores the feasibility of measuring the productivity of the military Research, Development, Test and Evaluation (RDT&E) program. The author formulates and estimates systematic relationships between the aggregate resources and products of the portions of the RDT&E program concerned with the development of new aircraft and missiles. These relationships trace the aggregate effects of different levels of these portions of the program and consequently measure the productivity of the related RDT&E resources. The relationships can be useful for showing the effects of RDT&E resources as instruments for achieving military security in a way that might be compared to the resources allocated to other instruments such as force procurement, force deployment, and intelligence.

DD FORM 1 NOV 65 1473

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400 Army-Navy Drive, Arlington, Virginia 22202

Contract DAHC15 67 C 0011
T-83

FOREWORD

This paper explores the feasibility of measuring the productivity of the military Research, Development, Test, and Evaluation (RDT&E) program. It was done as part of a larger investigation of the time-trends displayed by the resources that have been allocated to RDT&E and the products that have been generated by those resources. This work was performed under contract DAHC 15-67C-0011, T-83.

Much effort has been devoted to studying the development of specific weapon systems and the cost-time-performance results that were obtained from those individual development programs. However, there has been little study of any systematic relationships that exist between the aggregate resources and products of the overall RDT&E program or major portions of it. Such relationships measure the aggregate effects of different levels of the total program and consequently reveal the productivity of the RDT&E resources.

Along with actions such as the procurement and actual deployment of military forces, the military RDT&E program is one of the means that can be used to counter threats to U.S. security. A measure of the productivity of RDT&E resources should, therefore, be useful in formulating the budgetary decisions on the distribution of resources among the alternative actions that might be taken. In weighing the costs and results of the alternatives, the budget formulators have a better idea from the productivity measure of the general results they can expect from RDT&E resources and when they can expect them.

Marilyn Flowers was especially helpful with the study, commenting on the development of the analysis, reviewing drafts of the paper, and performing data handling and computations. I am particularly indebted to Professor Edwin Mansfield for his extensive discussions

on the study of R&D and his detailed suggestions on the particular framework devised for this exploration and drafts of the paper. Joseph Delfico and I. George Henry carried out the rather large order job of assembling the basic data.

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I

INTRODUCTION AND FINDINGS

A. PURPOSE OF THIS STUDY

This study is an exploratory investigation into measuring the productivity of the resources devoted to Defense Research, Development, Test, and Evaluation (RDT&E) in terms of the products of RDT&E that can be observed. Such measurement can be useful in a number of ways. For one, it can be used as an indicator to evaluate the past performance of the RDT&E program by showing the overall and incremental resource consumption of the actual results of RDT&E. For another, such measurement can provide helpful information for determining future allocations of resources to RDT&E when the RDT&E productivity is compared to the outcomes of alternative actions that might be taken to meet threats to U.S. security.

B. BACKGROUND

Basically, Defense RDT&E can be considered to be one of several inputs to the U.S. military posture, composed of the actions taken to ascertain military threats to the U.S. and actions taken in preparation to meet those threats.[1] When viewed in this way, RDT&E is much like the procurement, operation, and maintenance of the various kinds of existing military forces and can be regarded as both a substitute

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1. Strenuous advocacy for treating research and development programs in this way within the special missions of the different Government Agencies has been made by Dr. Donald F. Hornig and William M. Capron, among others. cf. U.S. Congress, House of Representatives, Committee on Government Operations, Hearings: The Federal Research and Development Programs: the Decisionmaking Process, 89th Cong., 2nd Sess., January, 1966, pp. 3, 4, 14-20.

for and a complement to these other force activities. Developing a new strategic offensive weapon system can be a substitute for procuring, replacing, or changing the mix of existing strategic weapons. Similarly, R&D performed to anticipate the new weaponry a potential enemy might be developing can be a substitute for military intelligence.

At the same time, RDT&E complements current forces. New equipment and procedures generated during RDT&E increase the options available for meeting a given spectrum of threats, increase the effectiveness of existing forces to meet those threats, and increase the range of threats that can be met successfully. Knowledge acquired in RDT&E can also be helpful in interpreting intelligence assembled on the development of specific capabilities by countries that might threaten U.S. security.

This study is directed principally at one problem that obscures analysis of RDT&E relative to current forces and evaluation of the resources to be devoted to RDT&E. In contrast to procurement or operations, there is little hard, quantitative evidence of what has been obtained or what can be expected from current RDT&E efforts. Once equipment is in production, a procurement program and budget can be formulated with relative certainty about the quantity that will actually be delivered. Casual observation indicates that RDT&E has produced much progress in the form of new equipment, new processes, and substantially advanced technical capabilities. However, little systematic measurement has been made of the progress or the costs that such progress has entailed.

To overcome this problem, more work must be done to estimate the "return" on DOD RDT&E. Most of the investigations of DOD RDT&E to date have focused on individual weapon systems or groups of specific weapon systems that <u>have been</u> developed.[2] In other words, these

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2. e.g., A. W. Marshall and W. H. Meckling, "Predictability of Costs, Time, and Success of Development," in <u>The Rate and Direction of Inventive Activity: Economic and Social Factors</u>, Richard R. Nelson, ed. (Princeton: Princeton University Press, 1962). (cont'd)

studies have directed their attention to the "successes" and the cost, performance, and schedule characteristics of the development of only these "successes".

Evaluation of the overall RDT&E program requires that account be taken of all the resources that have been devoted to RDT&E and the aggregate of results of RDT&E. This study is an exploration of this level of analysis.

Although the problem is posed in terms similar to those used to describe the relationship between the inputs and outputs of an ordinary production process, two features of the RDT&E process distinguish it from the ordinary production process. These features make estimation of any relationship among RDT&E inputs and products more difficult. First, the products of RDT&E are quite complex. They consist of advances in technology that are embodied in new items of equipment, new processes that permit production at lower costs, and new organizational concepts and strategies that are not embodied in new items of equipment or production processes. Moreover, these products are unique--only one of each new product or process is produced by the RDT&E process. Much RDT&E effort probably generates a mix of products, with individual efforts generating them in different proportions so that the product at any one time is difficult to measure.

Second, RDT&E is characterized by an extrordinary riskiness, since the outcome of a given effort cannot be predicted with precision. The nonrepetitive aspect of the RDT&E process certainly reinforces this characteristic and distinguishes RDT&E from the routine production process wherein additional experience generally permits closer control of inputs and outputs.

Robert Summers, "Cost Estimates as Predictors of Actual Costs: A Statistical Study of Military Development," in T. Marshak, T.K. Glennan, Jr. and R. Summers, Strategy for R&D, (New York: Springer-Verlag, 1967).

R.L. Perry, et al., System Acquisition Experience, Memorandum RM-6072-PR, The RAND Corporation, 1969.

Alvin J. Harman, A Methodology for Cost Factor Comparison and Prediction, RM-6269-ARPA, The RAND Corporation, 1970.

Merton J. Peck and Frederic M. Scherer, The Weapons Acquisition Process: An Economic Analysis, (Boston: Harvard University Graduate School of Business Administration, 1962).

C. STUDY APPROACH

This study is not intended to be an exhaustive investigation of all the factors that might affect the RDT&E process. A more complete analysis of the process and such important factors as differences in organizational concepts, differences in development strategy philosophies, and differences in the relative demand for improvements in weapons of various classes and applications will, of course, require a much more extensive effort.

The particular approach adopted consisted of (1) surveying studies that have been made of industrial research and development for findings that might be helpful in a study of the DOD RDT&E process and (2) formulating, estimating, and interpreting the relationships that might exist between the resources devoted to DOD RDT&E and the resulting RDT&E products.

Because of the diversity of results generated over the whole spectrum of the RDT&E program, it is not analyzed as a single unified process. Two types of effort, based upon the kind of weapons developed, were broken out for this exploratory investigation. These are (1) the development of new aircraft and (2) the development of new missiles.

The productivity concept employed, therefore, is based upon the new weapons developed and does not relate directly to a measure of military posture.[3] However, this concept can be a helpful first step in obtaining a clearer picture of the trade-offs that must be considered between (1) current force changes and (2) the development of new weapons in budget deliberations.

D. STUDY FINDINGS

This study shows the following:

- That the models developed to estimate the systematic relationship between industrial R&D effort and output are helpful frameworks for analyzing the productivity of military RDT&E.

3. While some measures of relative posture are used by DOD for specific program categories, such as strategic offensive forces, these have not been combined in any overall measure of military posture.

- That these techniques are particularly appropriate for analyzing the productivity of components of the overall military RDT&E program.

Effort was focused primarily upon estimating the productivity of (1) fiscal obligations made for the development of aircraft in terms of the number of new aircraft brought to initial operational capability and (2) fiscal obligations made for the development of missiles in terms of the number of new missiles brought to initial operational capability (IOC).[4]

The estimates support the following propositions:

- The outputs of aircraft or missiles in a particular year depend upon the overall obligations made for the development of these types of weapon systems in the current and three prior fiscal years, the productivity of the earlier years' obligations being somewhat lower.
- Current output is related inversely to the number of new systems brought out in the previous two years.
- The overall program costs of developing representative missile or aircraft systems have been increasing.

Illustrative of these estimates is the implication that by 1970 an annual investment of about $1,500 million in the development of aircraft and related equipment would have been expected to generate one new aircraft per year. A total annual investment of about $1,800 million would have been expected to produce two new aircraft per year.

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4. Note that this was not intended to trace the costs of specific weapon systems but to analyze the productivity of the total resources devoted to the development of aircraft and those devoted to the development of missiles.

II

SURVEY OF STUDIES OF INDUSTRIAL RESEARCH AND DEVELOPMENT

There is little evidence that systematic studies have been conducted at the aggregative level into the productivity of the DOD RDT&E program. As background for analyzing the relationship between the resources devoted to RDT&E and the observed RDT&E products, a survey was made of studies conducted on the productivity of industrial R&D.

A. PURPOSE OF SURVEY

To the extent that the DOD and industrial R&D programs have analogous objectives and similar resource-allocation problems, studies of industrial R&D should provide background on a number of areas of interest for this study.[1] These areas include (1) approaches that might be taken to study the relationship between the inputs and outputs of RDT&E, (2) quantitative measures of RDT&E products, (3) the aspects of the structure and operation of the R&D process that would be important for performing analysis at this level, and (4) the factors that should be taken into account in such an analysis.

B. CLASSIFICATION OF STUDIES

For this survey, the studies of industrial research and development have been classified according to two characteristics, (1) the economic unit whose behavior was analyzed, and (2) the measure of R&D product used in the study.

The economic units represent three general levels of economic activity: the overall economy, industries or sectors, and individual companies.

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1. cf. Edwin Mansfield, Jerome Schnee, and Samuel Wagner, Overruns and Errors in Estimating Development Cost, Time, and Outcome. IDA Economic Papers, Arlington, Virginia: IDA, September, 1971.

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The R&D products fall into one of the following two subclasses, based upon the stage in the development-production sequence at which they are defined and measured: (1) the ultimate output produced and marketed by the economic unit and (2) the products generated more immediately by the R&D process. For the overall economy, the ultimate output was generally the Gross National Product. The ultimate output of industries or companies was usually some measure of total production or value added (sales value of production less the costs of purchased goods).

As measures of output more immediate to the R&D process, the investigators generally used counts of patents issued, inventions, innovations, or some other measure of new products generated by the economic unit.

C. EXAMPLES OF STUDIES OF INDUSTRIAL R&D

Table 1 contains a list of the studies of industrial R&D that were surveyed. These studies are grouped first according to the economic unit upon which they focus. Within that grouping, they are sorted according to whether they measure R&D product in the ultimate output of that unit or by some measure associated more immediately with the specific R&D effort.

D. RESULTS

Three aspects of the studies surveyed have been investigated in detail. Features of the R&D products used in the studies have been analyzed. The specific relationships that have been estimated between the resources devoted to R&D and the resulting R&D products are reported, and some implications of these estimates are drawn. The structure of the time lags between the application of R&D effort and the emergence of the R&D product is reviewed separately.

1. R&D Products

Because of difficulties with the definition, observation, and measurement of the products of R&D, the measures used in the studies

Table 1

STUDIES OF INDUSTRIAL R&D

Item	Author	Economic Unit	R&D Product
1.	Fellner (Ref. 1)	Overall Economy	Ultimate Output GNP
2.	OECD (Ref. 10)	Overall Economy	Immediate Output Innovations, Patents, Receipts for licenses
3.	Griliches (Ref. 4)	Industry agriculture, by state	Ultimate Output Total output per farm
4.	Mansfield (Ref. 9, Ch. 4)	Industry 10 manufacturing industries	Ultimate Output Industry output
5.	Leonard (Ref. 11)	Industry 16 manufacturing industries	Ultimate Output Growth of each industry's output
6.	Terleckyj (Ref. 3)	Industry 20 manufacturing industry groups	Ultimate Output Total input productivity advance
7.	Schmookler (Ref. 2)	Industry cross section of several industries	Immediate Output Patents, important inventions
8.	Mansfield (Ref. 9, Ch. 4)	Company 10 chemical and petroleum companies	Ultimate Output Company output
9.	Minasian (Ref. 5)	Company 17 chemical companies	Ultimate Output Company value added
10.	Grabowski (Ref. 7)	Company 27 chemical and drug companies	Ultimate Output Company sales growth
11.	Scherer (Ref. 8)	Company 352 companies in 14 industries	Immediate Output Patents granted
12.	Comanor (Ref. 6)	Company 57 companies in pharmaceutical industry	Immediate Output Dollar sales of new products in first two years arketed
13.	Mansfield (Ref. 9, Ch. 2)	Company 10 chemical companies, 8 petroleum companies, 11 steel companies	Immediate Output Major inventions and innovations

surveyed are not completely unequivocal indexes of the outputs generated by R&D effort. However, the measures that have been available and used are probably no more misleading when analyzed properly in this particular type of study than they are in other types of studies of production and market operations to which fairly high confidence is usually attached.

In general, the measures of R&D product that are based upon the ultimate output of the economic unit incorporate the very important production and marketing tests that should be applied to any proposal stemming from an R&D effort. These tests are critical in a commercial context to separate the truly productive R&D effort from the failures. The latter are much like manufactured items that come off the production line but, because they do not pass quality inspection, are scrapped. Like the scrapped manufactured item, the R&D failure can hardly be counted as a useful product.[2]

On the other hand, the ultimate output of the economic unit is usually affected by a host of non-R&D factors. With few exceptions, isolating the impact of the R&D effort on that output requires a fairly complicated untangling of the effects of many of these factors.

R&D products based on measures of outputs more immediate to the end point of the R&D process are probably affected by fewer non-R&D factors than the ultimate output measures. Consequently, they may be more directly and less complicatedly associated with the R&D effort that has been expended. However, the immediate output measures do not usually incorporate the relevance tests that production and marketing apply to new concepts. Some of these measures in fact might be reflections of the resources devoted to R&D rather than reflections of the results. Also, the immediate output measures do not usually give any indication of the actual size and usefulness of the technical advance that is embodied in any single R&D product.

2. However, like the costly zero-scrap manufacturing strategy that can detract from company operating profits, an R&D strategy that does not allow for some failures may not be the most economical procedure for making technological progress.

Appendix A contains a more detailed description and commentary on the various measures of R&D product that have been used in surveyed studies of industrial research and development.

2. Relationships Between R&D Inputs and Products

In several of the studies of industrial research and development, the authors formulated and tested very specific functional relationships between their measures of R&D inputs and products. The implications of the estimates of these relationships are summarized below. More detailed descriptions and analyses of the relationships are contained in Appendix A.

On the basis of the nature of the estimated relationships the studies listed in Table 1 fall into a few general groupings. Among those relationships that focus on the ultimate output of the economic unit to measure the impact of R&D, two groups are distinguishable. The first of these has introduced the R&D inputs into the broader context of the unit's production function, which represents the effects of the more general set of inputs on the unit's output. Feliner (1)*, Griliches (3), Mansfield (4,8), Terleckyj (5), and Minasian (9), fall into this group. The second group, Leonard (5), and Grabowski (10), have instead tried to relate changes in the ultimate output of the economic unit to some measure of R&D effort.

The remainder of the studies listed in Table 1 focus on the R&D process itself and generally relate the immediate output of the process to some measure of resources devoted to R&D.

There are striking similarities and mutually supporting findings in these relationships. Quite notable is the extent of agreement on the direction and nature of the impact of R&D effort on the ultimate output of industries and individual companies when that impact was estimated by incorporating the R&D inputs into overall production relationships.

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* Numbers shown in parentheses in this paragraph refer to item numbers on Table 1.

In general, the studies that tried to trace the impact of R&D effort through the ultimate output of the overall economy, of specific industries, and of individual companies agree that the "return" on investment in R&D is relatively high.

Also notable is the extent of the mutual reinforcement in those studies that have attempted to isolate the R&D process by concentrating on measures of R&D product more immediate to the end-point of the process. In this particular context, the investigators fairly well agree that the largest companies and large scale R&D efforts may not generate more R&D product per unit of effort.

However, the estimated relationships should be interpreted with some caution. The quantitative estimates that have been reported were derived from observations of what actually took place over a cross section of economic units or over a number of years. Projections that the same response rates could be expected now or sometime in the future can only be tentative because some factors not taken into account in these analyses could change.

3. Time Lags Between R&D Inputs and R&D Products

The studies surveyed incorporate a number of specific forms in the time lag that can occur between the expenditure of R&D effort and the emergence of the R&D product. These are summarized below. Appendix A contains a more complete discussion of them.

Three distinct patterns of lags are discernible in these studies. First, there is the pattern employed in Mansfield (4,8)* and Minasian (9). In it, the current R&D product (measured in terms of the final output of the economic unit) is affected by the cumulative R&D effort that has preceded it. The Minasian model treats R&D inputs in the more distant past as though they are as important to the process as are the more recent efforts. Mansfield's models on the other hand, treat the R&D contributions as though they depreciate in usefulness so that, while past effort is accumulated, it also has a declining impact.

* Numbers in parentheses refer to item numbers on Table 1.

A second pattern of lags is that employed by Griliches (3), Leonard (5), Grabowski (10), Comanor (12), and Mansfield (13). In this pattern, the R&D product (sometimes accumulated over a number of years) is related to an indicator of the level of R&D effort expended (most often an average) in a prior period. Frequently, the prior period over which the R&D effort is calculated overlaps the period during which the R&D product emerges, especially if the latter also is accumulated for a number of years.

In the third pattern, the R&D product of a specific year is related to the R&D effort expended in a specific year. Schmookler (7), and Scherer (11), employ this pattern. Schmookler relates the number of patents pending to the R&D expenditures in the same year. Scherer hypothesized that patent grants in 1959 were related to R&D employment in 1955. Scherer's rationale for using that specific lag was the contemporaneous lag between patent applications and patent grants in the U.S. Patent Office.

In addition to the time-lag information contained in the econometric studies surveyed, other evidence is available on the time span covered by the various phases of specific development projects carried out by industry. This evidence almost uniformly indicates that for individual projects the total elapsed time from inception to completion is quite short, usually less than 5 or 6 years. However, this information must be interpreted in light of two other points. First, the time span from inception to completion measures the outside limits of the time involved in the projects. The utilization of resources on individual projects will follow a pattern somewhat compressed within those limits. Second, the time patterns involved in individual projects, both successes and failures, aggregate in an unknown way into the time patterns underlying the productivity of an overall R&D program.

E. SUMMARY

This survey has focused on a few aspects of the R&D process investigated in a number of studies of industrial R&D.

First, some of the studies isolated the R&D process, emphasizing the influence of R&D effort upon measures of the immediate R&D output such as patents, innovations, or new-product sales. Other studies integrated the R&D process and the overall production process and traced the effects of R&D efforts on the ultimate product of the company, industry, or economy.

Second, the studies generally took into account a number of factors in testing the systematic relationship that exists between R&D effort and the output generated by R&D. In other words, some of these studies were concerned with explaining as completely as possible variations that had occurred in the pertinent measure of R&D output. Those studies that employed the ultimate product of the company, industry, or economy as the measure of R&D output considered the effects of changing the amounts and characteristics of the other inputs to the production process. The studies that investigated the relationship of R&D effort to immediate R&D outputs were also concerned with the scale of the R&D effort relative to the overall size of the enterprise, special industry characteristics, and special company features. The implications of changes in some of these factors were drawn.

Third, the precise structure of the lags between the expenditure of effort and the emergence of the R&D product varied somewhat among the studies. However, they invariably showed that current R&D output is dependent either upon the cumulative effort expended on R&D over some past period or upon some indicator of the level of effort that had been expended in some specific previous period.

III

ANALYSIS OF DOD RDT&E

In this section, an attempt is made to formulate an approach for analyzing the "return" on the DOD RDT&E effort, using the findings of the studies of industrial R&D where appropriate.

A. PURPOSE OF SECTION

The purpose of this section is to attempt to estimate the productivity of resources devoted to DOD RDT&E in terms of the flow of product from the DOD RDT&E process. Alternatively, this purpose can be viewed as trying to generate a "supply function" for DOD RDT&E. In this case, the "supply function" would depict how much RDT&E product might have been expected and when it might have been expected if a certain amount of resources had been devoted to RDT&E within some time pattern. Although somewhat imprecisely, such a "function" can be used to gain some indication of the "return" that might be imputed to DOD RDT&E.

B. ALTERNATIVE PERSPECTIVES FOR ANALYSIS

Paralleling the classifications of the studies of industrial R&D, an analysis of DOD RDT&E might be made from a number of different perspectives. One such general perspective parallels those studies of industrial R&D that focus upon the ultimate output of the economic organization as the product of its R&D effort. Within this perspective, subcases are possible. For example, in a national context, the DOD RDT&E effort contributes to overall national well-being in a manner analogous to the industrial R&D contribution to Gross National Product. Within the context of the operation of the Federal Government, the DOD RDT&E effort contributes to the

national security functions of Federal Agencies in a fashion that parallels the contribution of industrial R&D to industry output. Further, within the Department of Defense, the RDT&E effort contributes to the U.S. military posture in a fashion that resembles the contribution of a company's R&D effort to its final product.

A second general perspective on DOD RDT&E parallels those studies of industrial R&D that focus upon a measure of the immediate output of R&D as the product of industrial R&D effort. When the perspective is so limited to the R&D process, DOD RDT&E effort is considered to generate RDT&E products that correspond to the patent grants, major inventions, new product sales, or innovations generated by industrial R&D effort.

Because no convenient quantitative measures of national well-being, national security, or military posture have been devised, the scope of any quantitative analysis of DOD RDT&E must be restricted, in the first instance, to the RDT&E process and its product. Observed weapon systems and weapon innovations are the only available quantitative measures of RDT&E product and these do not readily translate into measures of military effectiveness or national security.

C. STRATEGY

The principal effort has been directed at analyzing, as intensively as possible, the available information on budgetary factors to estimate their effects on the flow of RDT&E output. This necessitated the exclusion from the analysis of the much wider range of factors that affect the RDT&E process and the flow of RDT&E product. Factors such as organizational concepts, development strategies, and development priorities, among others, were not considered. The objective was to isolate the effects of budgetary factors as well as possible, not to explain completely changes in RDT&E output.

Although data on the DOD RDT&E process satisfactory for current purposes are not generally available, some useable data on the development effort expended upon aircraft and missiles, and the

corresponding new systems have been assembled. (These data are described more fully below.) Since 1960, more than 50 percent of the total DOD RDT&E obligation has been devoted to the development of aircraft and missiles. While that effort was a substantial proportion of the total, the chosen scope obviously limits the representativeness of the analysis for all RDT&E.

D. HYPOTHESES

As an initial effort, the data available on aircraft and missiles have been used to test a number of basic hypotheses, some of which were suggested by the studies of industrial R&D, considered to be important for measuring the productivity of RDT&E resources.

First, the RDT&E product observed in a particular year depends in a systematic fashion upon the resources devoted to RDT&E over some preceding period. This product can be conceptualized as being generated by a development process that extends over a number of years, requiring some expenditure of effort in each.

Second, the effort expended upon RDT&E generates an inventory of new knowledge and technology. This inventory is not used in a continuous flow of new products but is drawn down periodically when a new weapon system constituting a technical advance is withdrawn from development to be placed in operation. Heavy draw downs occur when several new weapons are brought out within a short period, a year, for example. If new weapon systems subsequent to a heavy draw down are technically advanced over their predecessors, the contribution to the new systems by RDT&E effort expended in earlier prior years will be lessened.[1]

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1. This does not imply that earlier development work is not important to the development of more advanced systems. On the contrary, the earlier work undoubtedly adds to the cumulative fund of knowledge that points the way to the options that might be taken in the development of newer systems. However, the earlier work is also probably less systematically and easily linked to the more recent systems placed in operation. Further discussion of this point and related matter is contained in the sections below on the structure of the time lag with which RDT&E effort materializes.

Third, the productivity of a given level of expenditure of RDT&E effort varies in terms of the observable RDT&E product over time because of general price changes, trends in RDT&E process efficiency, and increasing product complexity. Just how this productivity varies is difficult to project. Casual observation indicates that prices and weapon complexity have generally been increasing over the period relevant to this study. This should result in the generation of less RDT&E product per dollar input with the passage of time. However, there is little indication of whether the operation of the RDT&E process can be characterized by a trend.

Following a review of the data that can be used to test and estimate these hypotheses, they are formulated in mathematical terms for statistical analysis.

E. RDT&E PRODUCTS

The definition and measurement of the DOD RDT&E products used here parallel the measures of output used in the studies of industrial R&D that emphasized the R&D products immediate to the development process. The latter studies used patent grants, new product sales, major inventions, and innovations. This study employs as measures of RDT&E output the new aircraft and missiles that first reached initial operational capability (IOC) in each year since 1951.

For our purposes, (IOC) occurs when the specific system first attains the capability to be employed effectively, including being manned or operated by a trained, equipped, and supported military unit.

The aircraft and missiles so classified are listed by calendar year in Appendix B. Table 2 contains a summary count of the number of aircraft and missiles that attained IOC in each year.

As a measure of RDT&E output, the number of aircraft and missiles attaining IOC possesses characteristics similar to the output measures used in the studies of industrial R&D. Like patent grants, inventions, and innovations, the number of new systems does not give any indication of the importance of the individual systems or of the

Table 2

AIRCRAFT AND MISSILES ATTAINING IOC

Calendar Year	Number of Aircraft	Number of Missiles
1951	1	0
1952	3	0
1953	2	2
1954	9	2
1955	4	2
1956	3	5
1957	1	0
1958	3	2
1959	9	6
1960	2	3
1961	1	6
1962	1	6
1963	1	2
1964	3	2
1965	2	1
1966	1	2
1967	3	4
1968	1	1
1969	0	1
1970	1	2

aggregation of these systems. In the case of aircraft, the yearly count can include items as diverse as heavy bombers, transports, fighters, and helicopters. The variation of craft across and within each of these classes is extremely broad. Moreover, the percentage breakdown of the count by these classes varies widely from year to year. Similarly, the annual count of missiles attaining IOC can cover the range of systems from ICBMs to vehicle- or hand-carried tactical, field missiles.

Also, like the industrial measures, the number of new aircraft or missiles is not an indicator of the extent of the technological advance that has been incorporated into these systems. At one extreme, an individual aircraft or missile might be composed largely of off-the-shelf technology. At the other, the new system may have required large extensions of the state of the art in several technologies. The RDT&E component of these extremes is quite disparate, yet a system at one extreme is treated as an RDT&E product equivalent to a system at the other extreme.

System counts also do not give any indication of the contribution of (1) RDT&E effort to military intelligence functions, or (2) of the technical progress that has been made by a particular effort but that is not reflected in any related weapon system brought to IOC. Moreover, this measure in no way traces the contribution of RDT&E to the U.S. military posture or to higher order national objectives.

However, in contrast to some of the industrial measures, the fact that the new systems do reach IOC gives some indication of the success of the product. To reach that point, a new weapon system must have passed through a screening process that can be thought to resemble the market test of success for new commercial products.[2]

On balance, the individual units of a new weapons count can only be a rough proxy measure of RDT&E product.

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2. Of course, the quality of that screening process might be highly debatable.

F. RDT&E INPUTS

Two characteristics of the RDT&E inputs used in the analysis of this section are discussed below: (1) RDT&E obligations, the measure of effort, and (2) the structure of the lags with which the impact of RDT&E effort might be observed.

1. RDT&E Obligations

Most of the studies of industrial R&D that were surveyed used some measure of dollar expenditures on R&D or some measure of manpower resources engaged in R&D as the measure of R&D inputs for their analyses. The measure of DOD RDT&E effort that was most satisfactory for purposes of this study was the obligations made in each fiscal year under the defense RDT&E appropriation. These obligations, reported by budget activities, show the obligations made for RDT&E on aircraft and related equipment and missiles and related equipment for each fiscal year.

Table 3 contains the sample of obligations data that were reported or could be readily estimated.

While these data are the best that could be obtained for this study, they nevertheless must be qualified. Obligations record the full amount of a contract that has been entered by the Government at the time the agreement is made. Obligations may therefore be a fair measure of the total development effort that has been performed, but they may not measure _when_ the development effort was expended. Actual expenditures, and probably effort, follow obligations with some time lag that may not be readily observable or regular. This time lag is probably affected by the urgency of the demand for the RDT&E products, the rate at which the capacity of the developer is being utilized, and the specific mix of products that is being developed.[3]

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3. cf. Harvey Galper and Edward Gramlich, "A Technique for Forecasting Defense Expenditures," _The Review of Economics and Statistics_, Vol. 50, No. 2, May 1968, pp. 143-155.

Table 3

RDT&E OBLIGATIONS FOR AIRCRAFT AND MISSILES

Fiscal Year	Aircraft (Millions of Dollars)	Missiles (Millions of Dollars)
1951	186	140
1952	230	239
1953	221	241
1954	270	232
1955	294	214
1956	353	280
1957	274	355
1958	442	903
1959	420	1,402
1960	333	1,542
1961	680	3,194
1962	615	2,752
1963	774	2,526
1964	993	2,141
1965	1,094	1,985
1966	1,256	1,997
1967	1,310	2,476
1968	1,209	2,506
1969	1,055	2,426
1970	1,457	2,185

The coverage of the obligations data as a measure of the RDT&E effort expended must also be qualified, however. In the early years included in the sample, coverage was irregular and incomplete. Without clear guidance, a common practice was to have much development work performed under procurement appropriations. The lines of demarcation between development and production will probably never be completely clear and other items of undercoverage (e.g., military personnel and military construction accounts) will probably persist. However, the undercoverage of obligations data from earlier published budget reports is supposedly fairly pronounced.

2. Lag Structure

As was pointed out in the last section, a number of different forms of lag structure have been employed in the surveyed studies of industrial R&D. However, most of them made current R&D product dependent upon the R&D effort expended over a number of prior years. Moreover, the productivity of any specific R&D effort declined with respect to current R&D product as the time by which that effort preceded the current period increased. More specific evidence would be useful for narrowing down the prior year at which the effect of RDT&E effort on current RDT&E product is hardly noticeable and can, therefore, be ignored for our purposes.

For a number of types of weapon systems, Mansfield has reported the estimated lead times, extending from the preparation of project requirements to the first production models. These include: recoilless rifle, 4.3 years; medium tank, 4.3 years; destroyer, 5.1 years; transport plane, 5.3 years; bomber, 6.0 years; fighter, 7.3 years.[4]

Additional information indicates, as was the case for industrial R&D, that the significant portion of development expenditures is compressed into a shorter time span within the overall lead time. For example, Black and Foreman report for the Titan II ICBM that the employment of scientists and engineers by the project's contractor

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4. Edwin Mansfield, The Economics of Technological Change, p. 103.

was compressed into a few years subsequent to program approval.[5] Figures 1 and 2 depict the phases of the development program and show the progression of employment of scientists and engineers in these phases.

Characterizing by a short period the time lag between the expenditure of RDT&E effort and the generation of RDT&E product only indicates that the readily traceable dependence of that product is on recent obligations. It does not indicate that there is little need for earlier, more basic development work. Tabulations for a sample of the weapon systems investigated in Project Hindsight show that the traceable research and exploratory development work underpinning those systems generally involved well under 10 percent of the total RDT&E effort attributed to those systems. Most of those research and exploratory development efforts were not undertaken specifically for the systems in which their results were incorporated, but they supplied the technological alternatives considered in the systems' ultimate designs.

G. EXPERIMENTAL FUNCTIONAL FORMS

The surveyed studies of industrial R&D suggest several functional forms relating R&D inputs to R&D products. However, the data available for this study of DOD RDT&E lend themselves to only a few types of functional forms. One of these, incorporating the basic hypotheses discussed above, could be investigated intensively.

The following form is the principal one employed in this study:

$$N_y(W) = a_o + a_T T + a_{n1} N_{y-1}(W) + a_{n2} N_{y-2}(W) + \beta_o R_y(W) + \beta_1 R_{y-1}(W) + \beta_2 R_{y-2}(W) + \beta_3 R_{y-3}(W) \quad (1)$$

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5. Ronald P. Black and Charles W. Foreman, "Transferability of Research and Development Skills in the Aerospace Industry," contained in Applying Technology to Unmet Needs, Appendix Volume V of Technology and the American Economy, Report of the National Commission on Technology, Automation, and Economic Progress, Washington: February 1966, pp. V-75 to V-130.

where

$N_{y-i}(W)$ = the number of new weapon systems of type W that were brought to IOC in year y-i,

T = y-1950,

and

$R_{y-i}(W)$ = obligations made under the RDT&E appropriation in year y-i for development of weapon systems in type W.

The a's and β's are parameters to be estimated.

In this formualtion, the current and lagged values of $R_{y-i}(W)$ represent the hypothesis that current RDT&E product depends systematically upon the resources devoted to RDT&E over a preceding time interval. The lagged values of $N_{y-i}(W)$ represent the hypothesis that the inventory of new technology generated by RDT&E effort is drawn down in discrete intervals as new systems appear. Any trend in the productivity of RDT&E resources that might be present should be captured by the variable T.

Variations on equation 1, employing different lengths of lags and various logarithmic forms, can also be devised readily for use in estimating.

H. ESTIMATION TECHNIQUES

Two statistical estimation techniques were used to test and estimate the parameters in the principal functional form studied: standard multiple regression estimation and polynomial distributed lag (PDL) estimation. The second of these constrains the coefficients of the variable that is included in the function with a distributed lag [$R_y(W)$, in this case] so that they fall on a prespecified interpolation polynomial.[6] The structure of the lags and the patterns of the coefficients in the studies of industrial R&D that were surveyed suggest that the PDL estimator is appropriate in the present context.

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6. cf. Shirley Almon, "The Distributed Lag Between Capital Appropriations and Expenditures," Econometrica, Vol. 33, No. 1, January 1965, pp. 178-182.

I. RESULTS

Several variations on the principal functional form were tested and estimated by both estimation techniques. However, only those results that appear to be most meaningful for our purposes are reported and discussed below.

Using the number of new systems brought to IOC in any year as the measure of RDT&E product, and the corresponding RDT&E obligations as the measure of effort in equation 16, the following results were obtained:

<u>For aircraft</u>

$$\begin{aligned} N_y(A) &= \underset{(4.45)}{10.75} - \underset{(-2.22)}{0.88T} - \underset{(-0.89)}{0.20N_{y-1}(A)} - \underset{(-1.85)}{0.41N_{y-2}(A)} + \underset{(1.18)}{0.0024R_y(A)} \\ &\quad + \underset{(1.18)}{0.0018R_{y-1}(A)} + \underset{(1.18)}{0.0012R_{y-2}(A)} + \underset{(1.18)}{0.0006R_{y-3}(A)} \qquad (2) \end{aligned}$$

(t values in parentheses)

$$R^2 = 0.55$$

where

$N_{y-i}(A)$ = the number of new aircraft brought to IOC in year y-i,

$R_{y-i}(A)$ = obligations entered under the aircraft and related equipment budget activity of the RDT&E appropriations, in year y-i.

<u>For missiles</u>

$$\begin{aligned} N_y(M) &= \underset{(3.16)}{6.70} - \underset{(-2.31)}{0.60T} - \underset{(-0.90)}{0.27N_{y-1}(M)} - \underset{(-1.36)}{0.40N_{y-2}(M)} + \underset{(2.16)}{0.0013R_y(M)} \\ &\quad + \underset{(2.16)}{0.0010R_{y-1}(M)} + \underset{(2.16)}{0.0006R_{y-2}(M)} + \underset{(2.16)}{0.0003R_{y-3}(M)} \qquad (3) \end{aligned}$$

$$R^2 = 0.32$$

where

$N_{y-i}(M)$ = the number of new missiles brought to IOC in year y-i,

$R_{y-i}(M)$ = obligations entered under missiles and related equipment budget activity of the RDT&E appropriations in year y-i.

The numbers in parentheses below the coefficients of the equations are the values of the t-statistic for each coefficient. On the basis of a one-tailed test with eleven degrees of freedom, a t-value as high as 2.2 could result with a probability of about 0.03 from a sample of unrelated variables. A t-value as high as 1.2 could result with a probability of about 0.13 from such a sample. These measures of significance are offered, although there is some doubt that the standard tests of significance can be applied with the usual meaning to the coefficients estimated for the lagged variables by the PDL method because of the constraints that it imposes upon those coefficients.

Both equations 2 and 3 were estimated by the PDL estimation technique. Ordinary least squares estimates of the multiple regression function were generally less satisfactory. The R_{y-i} variables, especially, are highly collinear so that the least squares estimates are extremely variable and therefore less reliable. The PDL estimation technique is particularly good for handling this kind of problem while preserving degrees of freedom.

The coefficients of determination, R^2, for equations 2 and 3 indicate that a substantial portion of the variation in the adopted measure of RDT&E product is not explained by the RDT&E obligations. This should be expected, however, from (1) the severe qualifications made on the system counts data as a measure of RDT&E product and the obligations data as a measure of RDT&E resources and (2) the necessary exclusion of several important factors from the estimating relationships. However, on the basis of this criterion, the estimated

equations compare favorably with some of the relationships estimated in studies of industrial R&D.[7]

Both equations appear to underestimate the number of new systems when the actual number is at the higher end of the sample range and overestimate the number of new systems when the actual number is at the lower end of the range. Inasmuch as weapons of widely divergent sophistications are combined in the sample, the equations might be speculated to overestimate the costs of small technical advances and underestimate the costs of large technical advances. Inspection of the basic data indicates that technical advance must not be strongly related to the type of aircraft or missile brought to IOC, however. There is no tendency evident for equation 2 to overestimate the number of new aircraft when particular types of aircraft are among those actually brought to IOC. Also, the estimates from equation 3 do not show a tendency to over- or underestimate the number of new missiles in any relationship to the pattern of the actual missiles brought to IOC.

The actual and estimated values of the numbers of new systems brought to IOC in each year, shown in Table 4, indicate that both equations 2 and 3 fit the data somewhat more tightly over the latter parts of the samples. For equation 2, the average absolute deviation of the actual number from the estimated number in the first 10 years of the sample is 1.8; for the last 10 years that average dropped to 0.7. Likewise, in equation 3, the average of the absolute deviations in the first 10 years is 1.6; it dropped to 1.2 in the last 10 years.

Although the coefficients in equations 2 and 3 are not uniformly significant, their signs are generally consistent with the basic hypotheses that were being tested about the RDT&E process. Both equations illustrate the dependence of the current year's RDT&E product upon the resources devoted to RDT&E over a number of previous years.[8]

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7. cf. Equations 4, 7, 8, 9, and 10 in Table A-2.

8. The R_y variables are measured by fiscal year, whereas the weapon systems reaching IOC are counted on a calendar year basis. Consequently, the current product is already lagged somewhat from the measure of current input.

Table 4

ACTUAL vs. ESTIMATED VALUES OF N_y

Year	Aircraft		Missiles	
	Actual $N_y(A)$	Estimated $N_y(A)$	Actual $N_y(M)$	Estimated $N_y(M)$
1954	9	7.0	2	4.5
1955	4	5.3	2	3.1
1956	3	2.8	5	2.6
1957	1	4.2	0	1.3
1958	3	4.5	2	1.6
1959	9	4.2	6	3.7
1960	2	1.2	3	2.3
1961	1	0.0	6	3.6
1962	1	2.6	6	4.7
1963	1	2.7	2	3.3
1964	3	2.8	2	3.3
1965	2	2.3	1	3.4
1966	1	1.7	2	2.7
1967	3	2.2	4	2.6
1968	1	1.4	1	1.5
1969	0	0.0	1	1.2
1970	1	0.5	2	1.6

The declining values for the coefficients of the R_{y-i}, as i increases in both equations, indicate a decrease in the traceable influence of earlier RDT&E obligations on current output.

The signs of the coefficients of the lagged N_{y-i} variables in both equations are not at variance with the hypothesis that previous years' product draws down the technology that would otherwise be accumulating for current RDT&E product. However, the relationship between the coefficients of N_{y-1} and N_{y-2} in both equations is not generally clear. Although they are not significantly different, the coefficients of these variables indicate that the systems brought to IOC two years prior to the current year have a stronger effect on the inventory of technology than those introduced only the year before the current year.

Both equations indicate a negative trend in RDT&E product. This implies that developments in the general price level, changes in the complexity of weapon systems over time, and possible changes in the efficiency of RDT&E inputs have an aggregated net negative effect over time upon the number of new weapon systems that will be brought to IOC per dollar of RDT&E obligations.

J. IMPLICATIONS

More specific implications of these equations must be drawn cautiously. They have been estimated from data that extend over a relatively short time span and that require strong qualification as measures of RDT&E effort and product. They may describe relationships that have existed between these RDT&E inputs and products in the past but that would not mean they necessarily extrapolate as well into future circumstances. They must also be taken to be somewhat tentative. Further study could well turn up more satisfactory functional forms and estimating techniques.

The time trend is an extremely strong driving force in these equations. In equation 2, the coefficient of t implies that to maintain a "steady-state" flow of new aircraft from RDT&E, aircraft RDT&E obligations must be increased each year by the equivalent of

0.88 of the obligations needed to bring to IOC a "representative" aircraft of the beginning of the sample span. Such an annual increase would just compensate for the trends in the general price level, weapons complexity, and RDT&E process efficiencies.

The N_{y-1} and N_{y-2} variables also serve to cover somewhat the discretionary latitude that exists in timing the IOC of new systems. However, regardless of when a new aircraft is brought to IOC, over the following two years, the output of new aircraft will be decreased by 0.6 (0.2 + 0.4) of an aircraft from the level it would otherwise attain. This appears to indicate that using current technology to bring an airplane to IOC at present does not decrease the potential output of the future by the same amount. Such a condition might be further interpreted to mean that there is sufficient spin-off and carry over in the aircraft RDT&E process for the inception and partial development of a new item.

Equations 2 and 3 indicate that R_y, R_{y-1}, R_{y-2}, and R_{y-3}, the obligations in the various years, are all substitutable for each other to some extent in the generation of current RDT&E product. However, the declining coefficients imply that a dollar-for-dollar substitution cannot be made between any two years. For example, taking a million dollars from 1974 aircraft obligations and increasing 1973 obligations by the same amount will not have a neutral impact on the output of 1974. In fact, much more would have to be added to the 1973 obligations to maintain a given 1974 output.

How possible substitutions might work out under the productivity conditions depicted in equation 2 is shown in Table 5.[9] The alternatives on the left of the table take the immediate, previous conditions as the point of departure and show some different patterns of obligations that might be used to obtain five new aircraft in the period from 1970 through 1974. One aircraft would come to IOC in

9. For these illustrative purposes, the standard error of the regression equation has been ignored. A much more elaborate simulation would be necessary to show how the introduction of the error term could affect the results.

Table 5

ILLUSTRATION OF AIRCRAFT RDT&E OBLIGATIONS
BASED ON EQUATION 2

Year	Alternatives				Steady-State	
	$N_y(A)$	Case 1 $R_y(A)$	Case 2 $R_y(A)$	Case 3 $R_y(A)$	$N_y(A)$	$R_y(A)$
1970	1*	1457*	1457*	1457*	1	1563
1971	1	1792	1792	1792	1	1710
1972	1	1921	1921	1921	1	1857
1973	0	2100	1921	1750	1	2004
1974	2	2338	2471	2600	1	2151

*Actual values.

1970, 1971, and 1972; two would come out in 1974. That pattern of output might be thought of in terms of what is actually desired from the RDT&E process, not necessarily the number estimated from the equation. The equation would estimate some non-zero number for 1973 from the previous obligations. The three cases differ primarily in terms of the reliance that is placed on the last two years' obligations, representing different assumptions about the extent to which any single year's obligations might be changed from its predecessor. The main point, however, is that between Case 3 and Case 1 $R_y(A)$ was decreased by 262 but $R_{y-1}(A)$ had to be increased by 350 to maintain an output of two aircraft in 1974.

As a comparison, the "steady-state" condition shown in the right hand columns of the table does not take the immediate history as given but depicts a situation in which one aircraft has been brought to IOC each year over some past period. Between 1970 and 1974, the same number of aircraft are brought to IOC, but these are distributed equally among the years.

Care should be exercised in trying to infer from the equations any single "correct" pattern of obligations that should be used to generate future RDT&E products. At any rate, they should not be

interpreted as implying that since earlier RDT&E effort contributes only in a depreciated way to current RDT&E product, the cheapest way to generate current product is therefore to compress as many of the obligations as possible into the nearest fiscal year. The RDT&E process obviously does not operate that way. The estimated equations are based on the assumption that the process will continue in a manner similar to the period of the sample. Earlier effort is just not as readily or as systematically traceable to current product. Moreover, some evidence exists that strong surges in RDT&E effort may be associated with declining productivity of the resources applied.[10]

K. SUMMARY

In this section, some of the findings of the survey of studies of industrial R&D were applied to testing whether there exists a

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10. For example, equations 9 and 10 in Table A-2. Some additional preliminary work has been done with the DOD RDT&E data in this regard with the following results.

$$N_y(A) = \underset{(3.55)}{8.99} - \underset{(-1.89)}{0.85t} - \underset{(-0.78)}{0.20N_{y-1}(A)} + \underset{(1.33)}{0.0074S_y(A)} + \underset{(1.20)}{0.0076D_y(A)} - \underset{(-0.51)}{0.00002D_y(A)^2} \qquad (2)$$

$$R^2 = 0.50$$

$$N_y(M) = \underset{(2.69)}{5.15} - \underset{(-1.78)}{0.44t} - \underset{(-1.26)}{0.36N_{y-1}(M)} + \underset{(1.70)}{0.0023S_y(M)} + \underset{(2.28)}{0.0038D_y(M)} - \underset{(-0.85)}{0.0000008D_y(M)^2} \qquad (3)$$

$$R^2 = 0.57$$

where

$$S_y = 0.333 \sum_{i=1}^{3} R_{y-i}$$

$$D_y = R_y - S_y.$$

systematic relationship between the resources devoted to military RDT&E and the number of new weapon systems attaining IOC.

Despite some formidable shortcomings in the measures of RDT&E effort and RDT&E product, functional forms suggested by the studies of industrial R&D yielded some significant results. The estimated equations do not explain completely the observed variations in the RDT&E product, but they do give a measure of the productivity of RDT&E resources devoted to the development of aircraft and missiles in terms of the number of new aircraft and missiles reaching IOC. Resources in the form of obligations in the current and three preceding fiscal years affect the number of systems attaining IOC currently. The influence of obligations on current output depreciates according to how much earlier they were made relative to the current period. The equations can, therefore, be used to gain some insight into the impact on the generation of new systems that might be expected from shifts of obligations among various fiscal years.

Time trends are significant driving factors in these equations, indicating that the current-dollar development costs of new aircraft and missiles have been increasing. However, this trend could not be separated into the portions attributable to general price level increases, growing weapon complexity, or possible changes in RDT&E process efficiencies.

The development of aircraft and missile technology appears to be cumulative as sequential obligations are made, being used up to some extent as it is incorporated into new systems reaching IOC. However, the introduction of a new system does not deplete the future output of new systems by the same amount. Possibly, this signifies that the carryover and spin-off from the development of a new system provide, for some short period, a base from which another system could be initiated.

IV

FURTHER WORK

The results obtained in this study are sufficiently promising that they indicate further work should be done to study the relationship of overall RDT&E effort to the technological advance it generates.

First, such work should probably focus on the inputs and products of overall development programs for specific types of weapons, such as aircraft, missiles, or ships. In so doing, a more concentrated effort can be made on the definition and measurement of the relevant inputs and products of the RDT&E process. This effort should be directed at a better suited time-phasing of the resource data so that both they and the output measures are based on a similar fiscal or calendar period. Also, more effort should be made to have the input measure reflect the resources that have actually been devoted to activities that are commonly accepted as being in the nature of RDT&E. Reference was made above to the fact that much development work has been done in the past under procurement authorizations. At the same time, both the time-phasing and completeness of the input measure might be improved if expenditure data rather than obligations were used.

Instead of simple counts of weapons or innovations, experimentation might be performed to devise measures of technologocal advance based on performance, operating, or technical parameters of weapons. In some analytical techniques, a number of such parameters could be used simultaneously as a description of technological advance without the necessity for their being reduced to a single dimensional measure.

More study should also be done to determine whether some other date than when a weapon system reaches IOC would be more appropriate for timing the RDT&E product.

Second, an effort should be made to devise a more complete "model" of the overall RDT&E process. The objective of this work would be to obtain a somewhat more generalized understanding of the process to determine the important factors at work besides those taken into account in this study. This effort would include devising ways to express the relationships among these factors and especially their effect upon the productivity of the resources devoted to RDT&E. Statistical estimation of these relationships could provide a better depiction of resource productivity and the variation observed in RDT&E output. As was pointed out above, no attempt was made to consider the effects of the urgency of the demand for new models of those particular types of weapons, the different development strategies, or the different administrative procedures. Nor was an attempt made to understand completely the overall RDT&E process in a way that would permit taking into account all the factors that should be considered.

This modelling effort will require a more thorough study of the planning and execution of the RDT&E program. The extensive case studies of weapon system developments and Terminal Reports from the Contractor Performance Evaluation Program should provide a starting point for this effort. However, because those studies focus principally on specific development efforts and completed RDT&E work, they should be supplemented by a broader study of the operation of the RDT&E program.

Third, additional work is also warranted on the formulation of alternate functional forms to express these relationships and the application of estimation techniques that can be used with the new measures and models. Once more extensive models are formulated, multivariate econometric methods capable of taking into account sets of simultaneous relationships among the factors might be found appropriate for making the statistical estimates. Also, some experimentation should be made with canonical correlation techniques and estimating procedures based on linear programming methods to handle the sets of input and product measures.

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Appendix A

STUDIES OF INDUSTRIAL RESEARCH AND DEVELOPMENT

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Appendix A

CONTENTS

Appendix A

STUDIES OF INDUSTRIAL RESEARCH AND DEVELOPMENT

This appendix contains somewhat more detailed descriptions and discussion of the set of econometric studies of industrial research and development that were surveyed as background to this study of the productivity of DOD RDT&E.

A1 CLASSIFICATION OF STUDIES

Review of a number of studies of industrial research and development indicated that they could be classified according to a few general characteristics. Two of these characteristics have been adopted for this survey, (1) the economic unit and (2) the R&D product that was analyzed in the study.

The economic unit used in each study is the administrative or functional establishment within which the R&D was considered to be performed or used for the purposes of that study. The studies surveyed based their observations on three different economic units (actually three different levels of aggregation of economic activity): the overall economy, industries or sectors, and individual companies.

The R&D products considered in these studies can be further characterized in terms of the stage in the development-production sequence at which they are defined and measured as the relevant R&D product. For this survey, the products generally fall into two subclasses, (1) output ultimately produced and marketed by or in the economic unit, and (2) the kinds of products that are more immediately associated with the R&D process.

Where the ultimate output of the economic unit was used as the relevant R&D product, the latter was quantified in terms of the gross national product for the overall economy, in terms of some measure of the total final output that an industry ships to others,

and in terms of some similar measure of a company's total final output. For industries and companies, these measures are generally total production (in dollars) or value added (sales value of production less the costs of purchased goods). In such studies, R&D is generally treated as part of the overall production process, the whole innovational process being an input used in the generation of the ultimate output.

Where a more immediate output of the R&D process is treated as the R&D product of the economic unit, the investigator has generally used some measure of the patents issued to the economic unit or the inventions, innovations, or other measures of new products made by the unit.

A third prevalent characteristic of the surveyed studies is less relevant to the present study. This characteristic was the specific policy issue that the investigator was attempting to address. In some cases, the investigator was trying to get some indication of the "return" to R&D and consequently some indication of whether too many or too few resources have been devoted to R&D. In other cases, the investigator was trying to obtain evidence of whether the size pattern of the companies was an important determinant of R&D effort and output or whether different industry structures might be compatible with similar progress.

A2 EXAMPLES OF STUDIES OF INDUSTRIAL R&D

Table A-1 contains a list of the studies of industrial R&D that were surveyed. These studies are grouped first according to the economic unit upon which they focus. Within that grouping, they are sorted according to whether they measure R&D product in the ultimate output of that unit or by some measure associated more immediately with the specific R&D effort.

A3 RESULTS

Three aspects of the studies surveyed have been investigated in detail, and features of the R&D products used in the studies have

Table A-1

STUDIES OF INDUSTRIAL R&D

Item	Author	Economic Unit	R&D Product
1.	Fellner (Ref. 1)	Overall Economy	Ultimate Output GNP
2.	OECD (Ref. 10)	Overall Economy	Immediate Output Innovations, Patents, Receipts for Licenses
3.	Griliches (Ref. 4)	Industry Agriculture, by State	Ultimate Output Total Output/Farm
4.	Mansfield (Ref. 9, Ch. 4)	Industry 10 Manufacturing Industries	Ultimate Output Industry Output
5.	Leonard (Ref. 11)	Industry 16 Manufacturing Industries	Ultimate Output Growth of Each Industry's Output
6.	Terleckyj (Ref. 3)	Industry 20 Manufacturing Industry Groups	Ultimate Output Total Input Productivity Advance
7.	Schmookler (Ref. 2)	Industry Cross Section of Several Industries	Immediate Output Patents, Important Inventions
8.	Mansfield (Ref. 9, Ch. 4)	Company 10 Chemical and Petroleum Companies	Ultimate Output Company Output
9.	Minasian (Ref. 5)	Company 17 Chemical Companies	Ultimate Output Company Value Added
10.	Grabowski (Ref. 7)	Company 27 Chemical and Drug Companies	Ultimate Output Company Sales Growth
11.	Scherer (Ref. 8)	Company 352 Companies in 14 Industries	Immediate Output Patents Granted
12.	Comanor (Ref. 6)	Company 57 Companies in Pharmaceutical Industry	Immediate Output Dollar Sales of New Products in First Two Years Marketed
13.	Mansfield (Ref. 9, Ch. 2)	Company 10 Chemical Companies, 8 Petroleum Companies, 11 Steel Companies	Immediate Output Major Inventions and Innovations

been analyzed. The specific relationships that have been estimated between the resources devoted to R&D and the resulting R&D products are reported, and some implications are drawn from these estimates. The structure of the time lags between the application of R&D effort and the emergence of the R&D product is reviewed separately.

A3.1 R&D Products

To some extent, most of these measures, as indicators of R&D, have both desirable qualities and inherent problems. In any investigation of industrial R&D, the analyst must weigh these features against each other carefully if he wants to depict accurately the process and the different relationships among the factors that are important in it.

Features of industrial R&D product measures can also be useful for gaining a better understanding of some aspects of the proposed measures of military RDT&E product. They can help point out both the strong qualities of these measures and the qualifications that must be made in their application to studies of the RDT&E process.

The review follows the same classification scheme that was used in the survey of studies of industrial R&D in Section 2. The first class of output measures is that set that treats R&D as part of the general production process, contributing to the ultimate product of the company, industry, or economy. The second is the set of output measures that tries to treat R&D as a separable process and views that process in terms of its immediate outputs and direct inputs.

A3.1.1 Ultimate Products

A3.1.1.1 Gross National Product. The Gross National Product (GNP) is the market value of the goods and services produced in the economy, excluding any allowance for capital usage. It is the basic measure most frequently used in studies of the overall productivity of the factors employed in the economy. When GNP is used to measure R&D product, the analyst generally attempts to isolate that portion of GNP, or its growth, that might be attributable to the R&D effort.

For the result of R&D effort to become part of the GNP, it must have the desirable property that it has passed strenuous tests of relevance. First, it is practical; it can be produced. Second, it is marketable; it is useful for satisfying some wants or needs.[1]

The GNP measure is particularly good at capturing and displaying the effects of cost-reducing new processes and managerial methods generated in R&D. These expand the capabilities of the current resources to produce goods and services for the economy.

However, the GNP measure does not do so well in recording the effects of R&D efforts embodied in new or improved products. The problem arises in the mechanics of trying to devise price indices whose application to monetary measures of national product would adjust for price changes over time and reveal developments in the real product of the economy. The result is that new products are counted only in terms of the amount of old products that could have been made by the resources devoted to the new products. The measure does not reflect the greater range of choice that the members of the economy have as a result of the new products and any implications the wider choice has for their economic well-being.[2]

GNP must, therefore, be interpreted cautiously as a measure of product from R&D activity. Gustafson has estimated that more than three-fourths of U.S. industrial research and development is directed to new products, as opposed to new internal production processes.[3]

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1. cf. Simon Kuznets, "Inventive Activity: Problems of Definition and Measurement," in Richard R. Nelson, ed., The Rate and Direction of Inventive Activity, A Report of the National Bureau of Economic Research, Princeton: Princeton University Press, 1962, pp. 19-24.

2. cf. Edward F. Denison, The Sources of Economic Growth in the United States, Committee for Economic Development, Supplementary Paper No. 13, New York: Committee for Economic Development, 1962, pp. 156-157, and Richard R. Nelson, "Technical Advance and Growth of Potential Output," in Wroe Alderson, et al., eds., Patents and Progress, Homewood, Illinois: Richard D. Irwin, Inc., 1965, pp. 154-155.

3. W. Eric Gustafson, "Research and Development, New Products, and Productivity Change," American Economic Review, Vol. 52, No. 2 May 1962, pp. 177-185.

Moreover, many factors besides the internal performance of R&D contribute to the growth of GNP or the amount of GNP generated per unit of labor. These factors include the amounts of equipment and other capital employed per worker, the educational level of the worker, transfers of technological advances among industries and countries, and worker turnover rates, among others. Isolation of the R&D component requires the untangling of all these influences, but untangling the various influences is difficult. In most studies, adjustments are made for changes in the other factors that are most readily measurable such as capital, education, turnover, etc. The residual growth or productivity that remains "unexplained" after the adjustment is usually imputed to be the contribution of R&D. The principal difficulty with this approach is that allowance is generally not made for possible interactions between the R&D and the other factors. For example, the amount of capital that can be employed per worker may actually have been changed as a result of R&D. In other words, the R&D expanded the technical-process options that producers could take and decreased the relative cost of more capital-intensive options so that producers were induced to employ them.[4]

Consequently, the isolation of the R&D component of GNP requires the use of rather complicated estimation techniques on fairly complex functional relationships that depict the workings of R&D in the context of these many factors.

A3.1.1.2 Industry Output. Industry R&D product has been measured in terms of the contribution made by the industry's R&D effort to the industry's final output, the latter measured in a single dimension. In other words, some of the final output is attributed to the R&D effort in the sense that R&D effort generates such output much like the resources that are employed in the production process.

As is the case with GNP and other measures based on the ultimate output of the company, industry, or economy, the results of R&D

4. cf. Richard R. Nelson, "Technical Advance and Growth of Potential Output," pp. 149-152.

activities must pass the tests of relevance to be included in this measure of product.

New, lower cost production processes generated by R&D activities are readily reflected in this measure as increases in the productivity of the other resources employed. However, difficulties similar to those discussed above with regard to GNP are also encountered in the reflection of new products by the industry output measure.

A number of factors influence industry output so that isolating the component attributable to R&D effort requires employing estimation procedures to untangle their effects. To factors such as those already mentioned in the review of the GNP measure of R&D output must be added the complications caused by shifts in the demand for the industry's products and changes in the industry's output mix.

A3.1.1.3 Company Sales. Company R&D product has been measured in terms of the component of company sales that might be traced to its R&D effort. For R&D activity to influence company sales, it must pass the relevance tests of production feasibility and marketability. Inasmuch as new products generated in the R&D effort may expand company sales, the effects of R&D directed at new products might be depicted in this measure. However, there is little chance that the effects of R&D aimed at new, cost-reducing processes will be captured by this measure unless they permit the company to increase its sales by expanding its share of the market. Greater profits at given sales levels would not show up as an R&D result.

The confounding of the effects of the several factors influencing company sales expansion is particularly severe. Factors parallel to those mentioned above with respect to GNP and industry output influence company sales. In addition, company sales include inventory adjustments and respond to factors related to the company's own sales promotion efforts. Changes in the structure of the company's industry and the company's position within the industry affect the development of its sales. Overall, the set of relationships within which R&D interacts with other factors to influence company sales appears to be especially complex.

A3.1.1.4 <u>Value Added</u>. Value added by a company or industry is the sales value of the company or industry production less the costs of materials and other produced inputs purchased on current account. It consists principally of the compensation made to basic labor, capital, and entrepreneurial inputs, as well as business tax payments. When value added is used as a measure of R&D output, an attempt is made to trace the portion of it that is attributable to the R&D effort expended.

For R&D effort to influence the value added, the results of the R&D must have passed the production feasibility and marketability relevance tests. Inasmuch as profits are a major component of value added, it should reflect both cost-reducing technological advances and new products generated by R&D activity.

As is the case for the other ultimate output measures of R&D product, value added is affected by a number of factors whose influence must be untangled if the impact of R&D is to be isolated. However, this does not seem to be so formidable for value added as it is for company sales.

Some of these factors affect even those industries that produce a fairly constant product mix over a relatively long time period, such as agriculture and the petroleum industry. Among these are cyclical and secular shifts in demand, changes in business taxes or the prices of basic factors such as labor and capital, and changes in the extent of the vertical integration of the company or industry. When the extent of vertical integration increases, formerly purchased materials costs are broken up into components of more basic material inputs and increments to value added.

If the product mix is subject to quite wide variations, shifts from material-input-intensive products to value-added-intensive products have the same effect as changes in the extent of the company's or industry's vertical integration.

A3.1.2 Immediate Products

A3.1.2.1 New Product Sales. The new product sales measure of R&D product consists of counting, for some period, the company or industry sales of new products that originated in R&D activity. Using this measure does succeed, to some extent, in isolating the R&D process and its impacts while preserving some of the desirable features of the ultimate product measures of R&D output. Obviously, such products have passed, at least partially, the production feasibility and marketability tests of relevance.

However, use of this measure also poses a number of problems. First, some defensible rationale must be made about the number of years over which the sales of the new products will be counted. Determining the relevant time period is not easy, especially in light of some other difficulties. Second, sales do not measure profitability. Products that generate losses should not be treated as equivalent R&D outputs to those having similar sales and positive profits. Third, sales data give no indication of the technological advance that is included in a product. A very slight change (such as dosage form) in a product that already has large sales might be contrasted as an R&D output with a product embodying a large technological advance and having relatively small sales (but a high margin). Incremental changes in products compound the difficulties of how to determine the relevant time period of new-product sales. Fourth, new-product sales miss entirely the class of R&D effort that is directed at generating lower cost processes for the production of old products.

A3.1.2.2 Patents. Some investigators of industrial R&D consider the number of patents issued to be a direct measure of R&D output. Patent applications, and patent grants, follow fairly closely on the end point of an R&D effort, but they are also made as a result of activities other than research and development.[5]

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5. Jacob Schmookler, Invention and Economic Growth, Cambridge, Mass.: Harvard University Press, 1966, pp. 25-29.

Use of patent applications or patent grants as a measure of R&D product poses a number of difficulties. First, there are a number of questions about the extent to which patent counts R&D activity. Second, there is doubt that patent counts give even the roughest indication of the usefulness of the covered inventive activity. Third, there is some question as to whether patent grants identify R&D output at all.

The general consensus appears to be that patent grants cover only an unknown portion of overall technological advance or R&D output. This stems largely from three factors: nonapplicability, government-sponsored research, and reluctance to patent. The results generated in basic research activities cannot be patented under the current laws. Consequently, any advances made in those activities will not be reflected in patent grants.

Government financing of research and development has increased since World War II to the point that it is the dominant source of funds for these purposes in the United States. To the extent that the use and dissemination of the results of the work carried on with this funding are generally controlled by the terms of the government grants and contracts, the performers of the work have little incentive to apply for patents on their results.

Apparently since the late 1930's, companies, and especially large companies, have been consciously not applying for patents when they have generated patentable items. A number of influences has worked in this direction. The processing time of an application in the Patent Office has increased significantly; consequently, any favorable commercial outcome from the new item has been largely accomplished before the patent grant. This has not been found to be an entirely disagreeable development so that companies have become more willing to rely upon the secrecy they can maintain about a discovery without a patent and work for a substantial head start on any competitors. In addition, companies have found the courts to be increasingly hostile toward upholding patents and especially

severe when patents have become a focal point in antitrust proceedings.[6]

A second major problem with using the number of patents as a measure of R&D output is the little information that the courts give with regard to the usefulness of the covered items. The novelty requirement for patentability obviously does not guarantee that the new item will be at all useful. In a very small sample of less than 100 patent grants, the estimated profits on individual patents in use ranged from $1,000 to $15,000,000; of those in use but showing losses, the mean loss was $94,000, and the median loss was $11,000.[7]

Finally, there is some question whether patents measure R&D product at all.

> ... patents may be a better index of research input than output. The correlations (of patents) with research and development employees are somewhat higher than with new product sales. The number of patents applied for may represent the effort expended by the firm in inventing, rather than the magnitude of the inventions which result from this effort. While this finding is highly tentative, it is supported by the likelihood that the significance of a patent in terms of input is less variable than its significance in terms of output.[8]

In other words, an underlying mode of operation in the research and development process may result in an application for a patent once a certain amount of effort is expended, regardless of the usefulness of the R&D results at that stage.

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6. cf. Simon Kuznets, "Inventive Activity: Problems...," pp. 36-37, and Jacob Schmookler, Invention and Economic Growth, pp. 30-39.

7. Reported in Jacob Schmookler, Invention and Economic Growth, p. 54.

8. William S. Comanor and F. M. Scherer, "Patent Statistics as a Measure of Technical Change," Journal of Political Economy, Vol. 77, No. 3, May/June 1969, p. 398.

A3.2 Relationships Between R&D Inputs and Products

In several of the studies of industrial research and development, the authors formulated and tested very specific functional relationships between their measures of R&D inputs and products.

A3.2.1 Mathematical Forms. The relationships are listed in Table A-2, arranged similarly to the list of studies in Table A-1. The quantitative aspects of the results of the Fellner, OECD, and Terleckyj studies are described in the following text.

Fellner (Item 1 on Table A-1) has attempted to sort out the various sources of the growth in total factor productivity unexplained by conventional input quantity and proportion changes. For 1953, he concluded that 5.9 percent of the private GNP was devoted to R&D, producing a 2.55 percent growth in GNP. The rate of return attributed to R&D was, therefore, 43 percent. For 1966, he estimated that 7.8 percent of the private GNP was employed in R&D. He attributed a 2.4 percent growth in the GNP to that investment in R&D, resulting in a rate of return of 31 percent. While recognizing that the average rate of return to R&D has probably declined over time, he remains willing to leave open the question of whether an expansion in the current R&D effort would produce smaller increments of return than the current marginal efforts.

In the OECD study (Item 2 on Table A-1), a cross section of 10 countries was investigated. Each country was assigned an index of its performance in technological innovation. This index is a composite of the country's ranking in six different indicators of technological innovation, including (1) share in 110 significant Post-World War II innovations, (2) receipts from patents, licenses, and know-how in 1963-64, and (3) the number of patents taken out in other countries in 1963. The composite index was then rank-correlated with other indicators which the study wanted to test as factors contributing to performance in technological innovation. Significant pair-wise correlations were found between the performance index and

Table A-2

RELATIONSHIPS BETWEEN R&D INPUTS AND OUTPUTS

Griliches, Industry: Ultimate Output (Item 3 on Table A-1)

Cross Section of U.S. Agriculture by 39 States in 1949, 1954, 1959

$$\log O_{it} = -0.017\, D_{54} - 0.006\, D_{59} + 0.059 \log R_{it} + 0.448 \log(LE)_{it}$$
$$(s.e.) = \quad (0.012) \qquad (0.017) \qquad (0.021) \qquad (0.063) \qquad (1)$$
$$+\ 0.164 \log M_{it} + 0.095 \log F_{it} + 0.145 \log B_{it} + 0.342 \log H_{it}$$
$$(0.034) \qquad (.013) \qquad (0.021) \qquad (0.027)$$
$$R^2 = 0.983$$

O_{it} = output per farm in State i, in year t

D_{54} = time dummy equal one when observation is for 1954

D_{59} = time dummy equal one when observation is for 1959

R_{it} = research and extension expenditures per farm in State i pertaining to year t. For 1959 and 1954, R_{it} is the average of expenditures made in years t-1 and t-6; for 1949, R_{it} is the average of these expenditures made in 1948 and 1945

$(LE)_{it}$ = product of labor days worked and education (in school years, per man) per farm in State i in year t

M_{it} = flow of machinery services per farm in State i in year t

F_{it} = weighted plant nutrients used per farm in State i in year t

B_{it} = stock of land and buildings per farm in State i in year t

H_{it} = expenditures on other inputs per farm in State i during year t

(s.e.) = standard error of regression coefficient

Table A-2 (Cont'd)

Mansfield, Industry: Ultimiate Output, 10 Manufacturing Industries, (Item 4 on Table A-1)

Disembodied Technological Change Assumption

$$Q(t) = A e^{a_1 t} \left[\int_{-\infty}^{t} e^{-\lambda(t-g)} R_o e^{(p-\sigma)g} dg \right]^{a_2} L^{\alpha}(t)\, K^{1-\alpha}(t) \qquad (2)$$

$Q(t)$ = output rate, in 1960 prices, at time t

$L(t)$ = labor input at time t

$K(t)$ = stock of capital (1929 prices) employed at time t

R_o = R&D expenditures, at base period o

P = rate of increase in R&D expenditures, current dollars

σ = rate of price increase of R&D

λ = annual rate of "depreciation" of an investment in R&D

a_1 = rate of technological change that would take place without any additional expenditure on R&D

a_2 = "elasticity" of output with respect to cumulated past net R&D expenditures

g = index of time prior to time t, over which R&D is accumulated

Mansfield could not estimate a_1 and a_2 directly but could estimate

$b' = a_1 = a_2 (p - \sigma)$ = overall rate of technological change

$$\hat{b}' = 0.011 + 0.212p \qquad (2\text{-}1)$$

Table A-2 (Cont'd)

Mansfield, Industry: Ultimate Output, 10 Manufacturing Industries, (Item 4 on Table A-1)

Capital-embodied Technolgical Change Assumption

$$Q(t) = AL^{\alpha}(t) \left\{ e^{-\delta t} \int_{-\infty}^{t} e^{(a_1/(1-\alpha)+\delta)v} \times \left(\int_{-\infty}^{v} e^{-\lambda(v-g)} R(g)dg \right)^{a_2/(1-\alpha)} i(v)dv \right\}^{1-\alpha} \tag{3}$$

Notation is the same as Equation 2 except

δ = annual rate of capital depreciation

$I(v)$ = gross investment in plant and equipment (1929 prices) at time v

v = index of time prior to time t over which capital has been accumulated

Note that the term within the braces, $\{ \}$, is the capital stock at time t, built up from the gross investment made during the time v before t with each prior gross investment incorporating the technology developed during the time g preceding it. The gross investment and the "investment" in R&D are depreciated at δ and λ rates, respectively.

In this case, Mansfield again estimated a measure of the overall technological change:

$$b = a_1 + a_2\,(p-\sigma) \tag{3-1}$$

$$\hat{b} = -0.044 + 0.668p$$

Table A-2 (Cont'd)

Leonard, Industry: Ultimate Output (Item 5 on Table A-1)

16 Manufacturing Industries

$$Y_1 = 19.80 + 8.98\,R_i + 0.38L_i + 5.75\,E_i \tag{4}$$

$$t = \quad (2.22) \quad (3.04) \quad (1.22)$$

$$R^2 = 0.70$$

Y_i = rate of growth of real output for the ith industry, 1957-59 to 1966-68

R_i = company R&D funds/net sales for industry i, 1957-63

L_i = increase in labor hours worked in industry i, 1956-58 to 1966-68

E_i = educational level of employees, median years schooling completed in 1960

t = value of the T-statistic for the regression coefficient

Table A-2 (Cont'd)

Schmookler, Industry: Immediate Output, 18 Industries (Item 2 on Table A-1)

$$Y = 1.3 + 0.529X \qquad (5)$$

$$R^2 = 0.85$$

Y = hundreds of patents pending in industry grouping in 1953

X = millions of dollars of R&D expenditures by companies in industry grouping in 1953

Table A-2 (Cont'd)

Mansfield, Company: Ultimate Output, 10 Chemical and Petroleum Companies (Item 8, on Table A-1)

Disembodied Technological Change Assumption

Using the relationship of Equation 2, Mansfield estimated for the sample of companies:

$$a_1 = 0.013 + 0.11\sigma$$
$$a_2 = 0.11 \qquad (2-2)$$

Mansfield, Company: Ultimate Output, 10 Chemical and Petroleum Companies (Item 8 on Table A-1)

Capital-embodied Technological Change Assumption

Using the relationship of Equation 3, Mansfield estimated for the sample of companies:

$$a_1 = -0.024 + 0.673\sigma \qquad (2-3)$$
$$a_2 = 0.673$$

Table A-2 (Cont'd)

Minasian, Company: Ultimate Output, 17 Chemical Companies, (Item 9 on Table A-1)

$$\log V_{ft} = -\log 0.019 + \Sigma d_f \log B_f + \underset{(0.076)}{0.820} \log L_{ft} + \underset{(0.081)}{0.156} \log K_{ft} + \underset{(0.015)}{0.113} \log R_{ft} \qquad (6)$$

(s.e.) =

$R^2 = 0.995$

V_{ft} = value added by company f in time period t deflated by company price index

B_f = dummy variable for company f

L_{ft} = total wage bill (including fringes) of company f, in time period t, deflated by wage rate

K_{ft} = gross rent and equipment and other real capital of company f in time period t

R_{ft} = the cumulative R&D expenditures of company f beginning with 1948 through time period t. t runs from 1948-1957

Table A-2 (Cont'd)

Grabowski, Company: Ultimate Output, 27 Companies in the Chemical and Drug Industries (Item 10 on Table A-1)

Form A

$$G_i\,(57\text{-}64) = -0.0080 + 0.0160D + 0.38G_i\,(50\text{-}56) + 0.52R_i - 0.0035R_i^2 \quad (7)$$

$$(\text{s.e.}) = (0.025) \quad (0.0088) \quad (0.14) \quad (0.48) \quad (0.0054)$$

$$R^2 = 0.47$$

Form B

$$G_i\,(57\text{-}64) = 0.0050 + 0.0150D + 0.39G_i\,(50\text{-}56) + 1.02R_i \quad (8)$$

$$(\text{s.e.}) = (0.0113) \quad (0.008) \quad (0.12) \quad (0.50)$$

$$R^2 = 0.46$$

G_i (57-64) = logarithmic growth rate of company i sales over 1957-1964

D = dummy variable indicating industry or company

G_i (50-56) = logarithmic growth of company i sales over 1950-1956

R_i = average number of professional R&D employees over the 1955-1960 period deflated by average sales over same period for company i

Table A-2 (Cont'd)

Scherer, Company: Immediate Output, Cross Section - 352 Companies in 14 Industries (Item 11 on Table A-1)

$$P_i/S_i = \sum_{I=1}^{14} d_I D_I - 12.54\, S_i + 61.33\, R_i/S_i - 2.84\, (R_i/S_i)^2 \qquad (9)$$

$$(\text{s.e.}) = \qquad (7.92) \qquad (7.87) \qquad (0.51)$$

$$R^2 = 0.54$$

P_i = patents granted company i in 1959

S_i = sales of company i in 1955, \$ billions

D_I = dummy variable indicating industry of company

= 1 if company i is member of Industry I

= 0 if company i is not member of Industry I

R_i = thousand R&D employees in company i in 1955

Table A-2 (Cont'd)

Comanor, Company: Immediate Output, 57 Companies in the Pharmaceutical Industry (Item 12 on Table A-1)

$$Y_i = 0.422 - 4.671\ R_i + 0.547\ R_i^2 + 0.0000344\ S_i - 0.000000128\ R_i S_i - 0.130\ D_i \qquad (10)$$

$$(\text{s.e.}) = (0.136)\ (1.285)\quad (0.107)\quad (0.0000083)\quad (0.000000031)\quad (0.040)$$

R^2 = 0.40

Y_i = total sales of all new chemical entities introduced by company i in the period 1955-1960 for the first two years after the individual products were introduced

R_i = average number of professional R&D personnel employed in 1955 and 1960

S_i = mean value of annual total prescription and hospital sales of company i between 1955 and 1960

D_i = diversification index

Table A-2 (Cont'd)

Mansfield, Company: Immediate Output, (Item 13 on Table A-1)

10 Major Chemical Companies

$$N_i = 2.38R_i + 0.404R_i^2 - 0.0247S_iR_i \quad (11)$$

$$(s.e.) = (0.041) \quad (0.075) \quad (0.0055)$$

$$R^2 = 0.99$$

N_i = weighted number of inventions or innovations made by company i between 1940-1957

R_i = average of company i expenditure on R&D in 1940 and 1950

S_i = company i sales in 1940

8 Major Petroleum Companies

$$N_i = 0.508 R_i \quad (12)$$

$$(s.e.) = 0.027$$

$$R = .99$$

N_i = weighted number of refining inventions and petroleum innovations carried out by company i between 1946 and 1956

R_i = average of company i expenditure on R&D in 1945 and 1950

11 Major Steel Companies

$$N_i = 1.19 R_i - 0.000548 S_iR_i \quad (13)$$

$$(s.e.) = (0.27)$$

N_i = number of important innovations made by company i between 1946 and 1958

R_i = average of company i expenditure on R&D in 1946 and 1950

S_i = sales of company i in 1946

(1) business financed R&D; (2) per capita expenditure on R&D; (3) expenditure on R&D performed by business; (4) Nobel Prizes in Chemistry, Physics, Medicine, and Physiology, 1943-67; (5) the number of companies with annual sales of $500 millions or more per million population; (6) the number of qualified scientists, engineers, and technicians in business per 10,000 population; and (7) the number of scientific abstracts.

In his cross section study of 20 industries, Terleckyj used the ratio of their R&D expenditures to their sales as a measure of research effort intensity. In a linear regression of the logarithms of the two variables, he estimated net coefficients indicating that a 0.5 percent increase in the rate of productivity growth results from an increase of 10 in research effort intensity. Because the two variables are related linearly in their logarithms, the effect of a given absolute increase in R&D on productivity declines at larger values of the intensity ratio.

A3.2.2 Implications of the Studies. Most of the studies contain rather precise quantitative indications of the response that might be expected in R&D product with changes in the effort expended upon R&D. Some of these are discussed below, but they should be interpreted with caution. The quantitative estimates that have been reported were derived from observations of what actually took place over a cross section of economic units or over a number of years. Projecting that the same response rates could be expected now or sometime in the future can only be tentative, because some factors that were not taken into account in these analyses could have changed systematically in the meantime.

Among those relationships listed in Table A-2 that focus on the ultimate output of the economic unit to measure the impact of R&D, two groups are distinguishable. The first of these has introduced the R&D inputs into the broader context of the unit's production function, which represents the effects of the more general set of inputs on the unit's output. Griliches', Equation 1; Mansfield's,

Equations 2 and 3; and Minasian's, Equation 6 fall into this group. The second group, Leonard's, Equation 4; and Grabowski's, Equations 7 and 8, have instead tried to relate changes in the ultimate output of the economic unit primarily to some measure of R&D effort.

The remainder of the relationships listed in Table A-2 focus on the R&D process itself and generally relate the immediate output of the process to some measure of resources devoted to R&D.

Mansfield's Equation 2, the disembodied assumption, and Minasian's Equation 6 are almost identical formulations. Both relate output to cumulative R&D effort. Mansfield's parameter a_2, elasticity of output with respect to cumulative past net R&D expenditures, matches precisely the comparable concept in the Minasian function. In the latter, Equation 6,

$$\text{Elasticity} = \frac{\partial \text{ Log } V}{\partial \text{ Log } R} = \frac{\partial V}{\partial R} \cdot \frac{R}{V} = 0.113. \qquad \text{(A1)}$$

Their independent estimates of these effects were virtually identical, 0.12 and 0.113, so that Mansfield substituted the Minasian value in his parameter representation, for his sample of ten companies, Equation 2-2 on Table A-2.

These results signify that a one percent increase in the R&D input (cumulative R&D expenditure) can be expected to generate a 0.1 percent increase in the final product of these companies.

When Mansfield assumed that the company's R&D makes it impact through being embodied in new capital equipment, his estimate of the elasticity of the company's output with respect to its cumulative R&D effort increased to 0.673.

In Griliches' function, Equation 1, the concept of R&D impact is quite similar to that used by Mansfield in Equation 2 and Minasian, except that past R&D expenditures are not accumulated by Griliches. In the latter's formulation, the elasticity of farm output with respect to R&D expenditures made in previous years is 0.06. A one percent increase in expenditures on research and extension services per farm eventually leading to a 0.06 percent increase in the output per farm.

One further step might be taken in the interpretation of the results of this group of studies. From the definition of elasticity in Equation A1, an expression can be derived for the derivative of the output in its original units with respect to the R&D input in its original units.

$$\frac{\partial V}{\partial R} = \text{Elasticity} \times \frac{V}{R} . \qquad \text{(A2)}$$

When the results of Equation 1, Equation 2-2, or Equation 6 from Table A-2 are substituted into Equation A2, they separately indicate the similar condition that, for the samples analyzed, at given levels of output equal increments in the research input add declining increments to the product. Of course, all other inputs are assumed to be held constant.

Inferences might also be made from Equation A2 about the effect of changing the overall scale of the unit on the productivity of R&D. A straightforward interpretation would be that an increase in V (in Minasian's notation), signifying that adjustments in any or all the inputs are admissible, would increase the productivity of R&D. This interpretation should be made with caution, however, for at least two reasons. First, there is the crucial question of whether any specific economic unit could maintain the same research intensity at different size levels. Second, in the estimating procedures, the "scale effect" is derived by observation across the sizes of the units included in the sample, that is, by what has actually been done. That is not necessarily an adequate reflection of what would happen if a single unit from the sample were to expand under its own management and planning concepts.

Leonard, Equation 4, and Grabowski, Equations 7 and 8, have also focused on the final outputs of industries and companies, respectively, to try to measure the impact of R&D effort. However, their approach differs rather markedly from that taken in the studies discussed immediately above. Leonard and Grabowski have tried to estimate

directly the contribution of R&D to changes that have taken place in their measures of the final output of the economic unit rather than untangle the effects of all factors influencing that output. Both indicate a significant positive relationship between their measures of R&D inputs and output. In Equation 7, Grabowski obtained some indication that the increase in output tails off as the R&D employee-sales ratio increases; but this is not statistically significant.

The remainder of the relationships listed in Table A-2 are directed at isolating the R&D process from the general operation of the economic unit. Each indicates a significant positive relationship between its measure of R&D input and its measure of R&D product.

The quadratic function fitted by Scherer, Equation 9, relates patent grants of companies in various industries to their R&D employees. Unlike Equations 1, 2, and 6, Scherer's suggests that at the lower relative levels of R&D input, the patent output increases, but at a decreasing rate, until a certain R&D intensity is reached. Once the company expands its R&D efforts beyond that intensity, additional units of R&D inputs only lead to a decline in the number of patents granted. The derivative of the function with respect to the R&D inputs is

$$\frac{\partial(P/S)}{\partial(R/S)} = 61.33 - 5.68\ (R/S).$$

This would indicate that the function reaches a maximum at an R&D intensity of 10.8 R&D employees per million dollars of sales.

Of course, these results should be interpreted cautiously and within the limits of the sample. However, they show, in general, that as company size is fixed and only the R&D input can be increased, diminishing returns are experienced. As adjustments in the company scale can be made, the productivity of a particular absolute level of R&D effort can be increased.

From Equation 10, Comanor calculated the elasticity of his output variable with respect to the R&D input variable at three company sizes, using the mean value of the actual R&D employment for companies of approximately those sizes from his sample. The following values resulted.

S	R	Elasticity
1,000	13.1	1.39
10,000	59.2	.61
50,000	353.3	.54

The percent increase in R&D output resulting from a one percent increase in R&D input declines as the size of the company increases.

He inferred that "while there are likely to be increasing returns to scale in R&D at low values of S, decreasing returns seem to be the case when S becomes moderately large." For a given company size, S, increases in R produce decreasing returns in Y until a minimum is reached; further increases in R produce increasing increments of output, Y. However, the minimum value is at higher levels of R for larger company sizes. In his sample, as company size increased, the additional output produced by an increment of R&D input declined.

In addition to the regression function that was described above, Comanor added dummy variables to his analysis to express threshold conditions for rates of expansion in the companies' R&D efforts.

G_1 = 1, if the ratio of the company's 1960 R&D employees to its 1955 R&D employees was less than or equal to 1

G_2 = 1, if the ratio was greater than 1 but less than 2.

The resulting coefficient of G_1 was 0.371; for G_2, the coefficient was 0.209. In addition, the constant of the overall regression function (which reflects the effects of expansion ratios greater than 2) decreased from 0.422 to 0.199. These would indicate that faster rates of expansion of the R&D effort had a depressing effect on the R&D output.

In his effort to focus more closely on the R&D process, Mansfield had to use relatively small cross sections of major chemical, petroleum and steel companies, Equations 11, 12, and 13. All three of his functions indicate that the number of equivalent innovations is positively related to expenditures on R&D, given the size of the company. In fact, for the chemical companies, Equation 11 suggests that as R&D expenditures are increased, the number of equivalent innovations increases more than proportionately. In petroleum and steel, the scale of the R&D effort does not have a discernible effect on the productivity of the R&D inputs. In the chemical and steel industries, company size has a depressing effect on the incremental inventiveness of an increase in R&D inputs at any given level of R&D inputs.

A3.3 Time Lags Between R&D Inputs and R&D Products

The studies for which functions are listed in Table A-2 reveal a number of forms and patterns of the time lag that can occur between the expenditure of R&D effort and the emergence of the R&D product. Table A-3 contains a list of the same studies for which functional relationships were reported in Table A-2, showing for each the nature of the sample that was used and some indication of the time lag from input to output that was formulated in each.

Three patterns of lags are discernible in these studies. First, there is the pattern employed in Mansfield's Equations 2 and 3 and Minasian Equation 6. In it, the current R&D product (measured in terms of the final output of the economic unit) is affected by the cumulative R&D effort that has preceded it. From Table A-2, it can be seen that the Minasian model treats R&D inputs in the more distant past as though it is as important to the process as is the more recent effort. Mansfield's models in Equations 2 and 3, on the other hand, treat the R&D contributions as though it depreciates in usefulness by some rate so that while past effort is accumulated, it also has a declining impact.

Table A-3

STRUCTURE OF TIME LAGS BETWEEN R&D INPUTS AND R&D PRODUCTS

Author	Table A-2 Equation	Sample	Timing of R&D Product	Timing of R&D Input
Griliches	1	Combined times series-cross section	1949 1954 1959	(1945+1948)/2 (1948+1953)/2 (1953+1958)/2
Mansfield	2 3	Combined time series-cross section	Current year of time series	Cumulative through current year of time series
Leonard	4	Cross section	Growth, 1957-1959 to 1966-1968	Cumulative 1957-1963
Schmookler	5	Cross section	1953	1953
Minasian	6	Combined time series-cross section	Current year of time series	Cumulative through current year of time series
Grabowski	7 8	Cross section	Growth, 1957-1964	Average of 1955-1960
Scherer	9	Cross section	1959	1955
Comanor	10	Cross section	Cumulative 1955-1960	(1955+1960)/2
Mansfield Chemicals	11	Cross section	Cumulative 1940-1957	(1940+1950)/2
Petroleum	12	Cross section	Cumulative 1946-1956	(1945+1950)/2
Steel	13	Cross section	Cumulative 1946-1958	(1946+1950)/2

A second pattern of lags is that employed by Griliches, Equation 1; Leonard, Equation 4; Grabowski, Equations 7 and 8; Comanor, Equation 10; and Mansfield, Equations 11, 12, and 13. In this pattern, the R&D product (sometimes accumulated over a number of years) is related to an indicator of the level of R&D effort expended (most often an average) in a prior period. Frequently, the prior period over which the R&D effort is calculated overlaps the period during which the R&D product emerges, especially if the latter also is accumulated over a number of years.

In the third lag pattern, the R&D product of a specific year is related to the R&D effort expended in a specific year. Schmookler, Equation 5, and Scherer, Equation 9, employ this pattern. Schmookler relates the number of patents pending to the R&D expenditures in the same year. Scherer hypothesized that patent grants in 1959 were related to R&D employment in 1955. Scherer's rationale for using that specific lag was the contemporaneous lag between patent applications and patent grants in the U.S. Patent Office.

Evidence other than that incorporated into the formulation of such input-product relationships has also been gathered to reveal, possibly more directly, the time that elapses between the inception and completion of industrial development projects.

In a study of the R&D projects of an electrical equipment manufacturer, Mansfield (Item 4 on Table A-1) surveyed 68 proposals to determine the elapsed time between their proposed beginning and estimated completion dates. The findings, summarized by number of projects and the proposed and budgeted expenditures, are shown in Table A-4.

In the same survey, but applying to a different number of projects, Mansfield found that once R&D projects are completed, the inventions resulting from them are applied with varying time lags. These results are summarized in Table A-5.

Estimates of the time that generally elapses from project requirement preparation to completion of the first production models have also been made for other types of products. For an electronic

Table A-4

NUMBER OF YEARS BETWEEN BEGINNING AND ESTIMATED COMPLETION DATE FOR 68 R&D PROJECTS

Number of Years	Number of Projects			Proposed Expenditures (Percent)			Budgeted Expenditures (Percent)		
	Division Requests (1963)	Division Requests (1964)	New Business (1963)	Division Requests (1963)	Division Requests (1964)	New Business (1963)	Division Requests (1963)	Division Requests (1964)	New Business (1963)
Less than 2.0	6	14	1	13	77	0	10	89	4
2.0 to 3.9	13	1	6	37	23	52	28	11	96
4.0 to 5.9	8	0	5	18	0	24	21	0	0
6.0 to 7.9	1	0	2	5	0	20	8	0	0
8.0 to 9.9	2	0	1	3	0	3	5	0	0
10.0 and over	8	0	0	23	0	0	28	0	0
Total[a]	38	15	15	100	100	100	100	100	100

Note: This is the completion date estimated by the department manager in 1963 or 1964 and not necessarily the completion date that was estimated when the project was begun.

a. Because of rounding errors, the figures in the last six columns may not always sum to 100.

Table A-5

ESTIMATED NUMBER OF MONTHS ELAPSING BETWEEN COMPLETION OF THE PROJECT AND APPLICATION OF THE INVENTION, 27 R&D PROJECTS

Number of Months	Number of Projects: Division Requests (1963)	Number of Projects: Division Requests (1964)	Proposed Expenditures (Percent): Division Requests (1963)	Proposed Expenditures (Percent): Division Requests (1964)	Budgeted Expenditures (Percent): Division Requests (1963)	Budgeted Expenditures (Percent): Division Requests (1964)
Less than 6.0	8	7	65	43	68	46
6.0 to 11.9	2	5	21	33	27	29
12.0 to 17.9	1	2	11	16	0	20
18.0 or more	1	1	3	8	3	5
Total[a]	12	15	100	100	100	100

Note: These estimates were made by the project evaluation group.

a. Because of rounding errors, the figures in the last four columns may not always sum to 100.

computer, this time interval is estimated at 5.0 years, for a telephone exchange 6.0 years, machine tool control equipment 3.0 years, and for a communications satellite, 5.0 years.[9]

These estimates establish the outside limits of the development period. However, additional evidence must be used to trace the time pattern of R&D expenditures. The additional evidence that exists indicates a compressing of R&D expenditures into a much shorter period within the outside limits of the development period. Norden reports that for major electromechanical systems, such as computers and calculators that take from three to five years to develop, more than 85 percent of the total effort may be expended within the middle 60 percent of the total elapsed time.[10] Although there is some disagreement about the precise amount that DuPont spent on the development of nylon, there is little dispute that the major expenditures for its development were made in the period between 1934 and 1938. Apparently, only relatively small amounts were devoted to the project from its inception in 1928 to the beginning of this period.[11]

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9. Edwin Mansfield, The Economics of Technological Change, New York: W. W. Norton & Company, Inc., 1968, p. 103.

10. P. V. Norden, "Curve Fitting for a Model of Applied Research and Development Scheduling," IBM Journal of Research and Development, Vol. 2, No. 3, July 1958, pp. 232-248.

11. cf. Richard R. Nelson, Merton J. Peck, and Edward D. Kalachek, Technology Economic Growth and Public Policy, Washington, D. C.: The Brookings Institution, 1967, pp. 90-92. Willard F. Mueller, "A Case Study of Product Discovery and Innovation Costs," Southern Economic Journal, Vol. 24, No. 1, July 1957, pp. 80-86.

APPENDIX B

U.S. AIRCRAFT AND MISSILES BROUGHT TO INITIAL OPERATIONAL CAPABILITY

Table B-1

MISSILE SYSTEMS IOC DATES

IOC Date	System	IOC Date	System
1953	AJAX	1961	TARTAR
1953	AIM-9	1961	AIM-7
1954	M-31	1961	QUAIL
1954	PETREL	1962	MINUTEMAN I
1955	REGULUS I	1962	TITAN I
1955	AIM-4	1962	SERGEANT
1956	MATADOR	1962	POLARIS A-2
1956	REDSTONE	1962	MACE
1956	TERRIER	1962	NUCLEAR BULLPUP
1956	FALCON	1963	TITAN II
1956	GENIE	1963	PERSHING
1958	HERCULES	1964	POLARIS A-3
1958	THOR	1964	CORPORAL
1959	ATLAS A-F	1965	AGM-45A
1959	SNARK	1966	MINUTEMAN II
1959	JUPITER	1966	REDEYE
1959	LACROSSE	1967	AGM 22
1959	TALOS	1967	STANDARD ER
1959	HAWK	1967	STANDARD MR
1960	POLARIS A-I	1967	AIM 54
1960	GAM-77	1968	SHILLELAGH
1960	BOMARC AB	1969	CHAPARAL
1961	ASROC	1970	TOW
1961	LITTLE JOHN	1970	SRAM
1961	M-50		

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Table B-2

AIRCRAFT IOC DATES

IOC Date	System	IOC Date	System
1951	H-12	1959	H-40
1952	HTK-1	1959	HH-52
1952	HRP-2	1959	H-43B
1952	F-10F	1959	B-8
1953	F-100	1959	B-8M
1953	F-102	1959	B-58
1954	F-104	1959	C-133
1954	F-101	1959	C-140
1954	F-11F	1959	P-3
1954	B-52	1960	CH-46
1954	B-57	1961	HU-2K-1
1954	A-3	1961	TH-55
1954	H-23B	1962	CH-47
1954	HOK-1	1963	C-141A
1954	CH-21	1964	QH-50C
1955	HSL-1	1964	CH-54
1955	HR2S-1	1964	YF-12
1955	F8U	1965	CH-53A
1955	F-105	1965	Air & Space 18A
1956	HSS	1966	OH-6
1956	F-106	1967	OH-58
1956	A-4	1967	F-111 (TFX)
1957	C-130	1967	AH-1G
1958	VERTOL 44	1968	FH 1100
1958	F-4	1970	C-5A
1958	F-5		